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(54) **FREQUENCY-DOMAIN TURBO EQUALIZATION, INCLUDING MULTI-MODE ADAPTIVE LINEAR EQUALIZATION, ADAPTIVE DECISION-DIRECTED CHANNEL ESTIMATION, ADAPTIVE NOISE VARIANCE ESTIMATION, AND DYNAMIC ITERATION CONTROL**

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See application file for complete search history.

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(57) **ABSTRACT**

Frequency domain based methods and systems to perform adaptive multi-mode pre-decoding linear equalization, adaptive channel estimation, turbo equalization, turbo equalization iteration control, and noise variance estimation. An adaptive linear pre-decoder equalizer may include a multi-mode equalizer, which may include a blind equalizer to determine initial equalization coefficients and a decision-directed equalizer to refine the initial equalization coefficients. Turbo equalization may include a dynamic iteration termination criterion and/or a fixed termination criterion. Turbo equalization may be based in part on an adaptive estimated noise variance. Methods and systems disclosed herein may be implemented with respect to single-carrier signals such as digital video broadcast signals.

18 Claims, 11 Drawing Sheets

100 —

Decision System 107
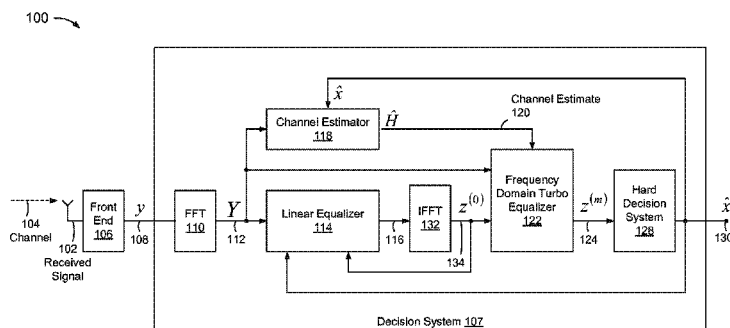
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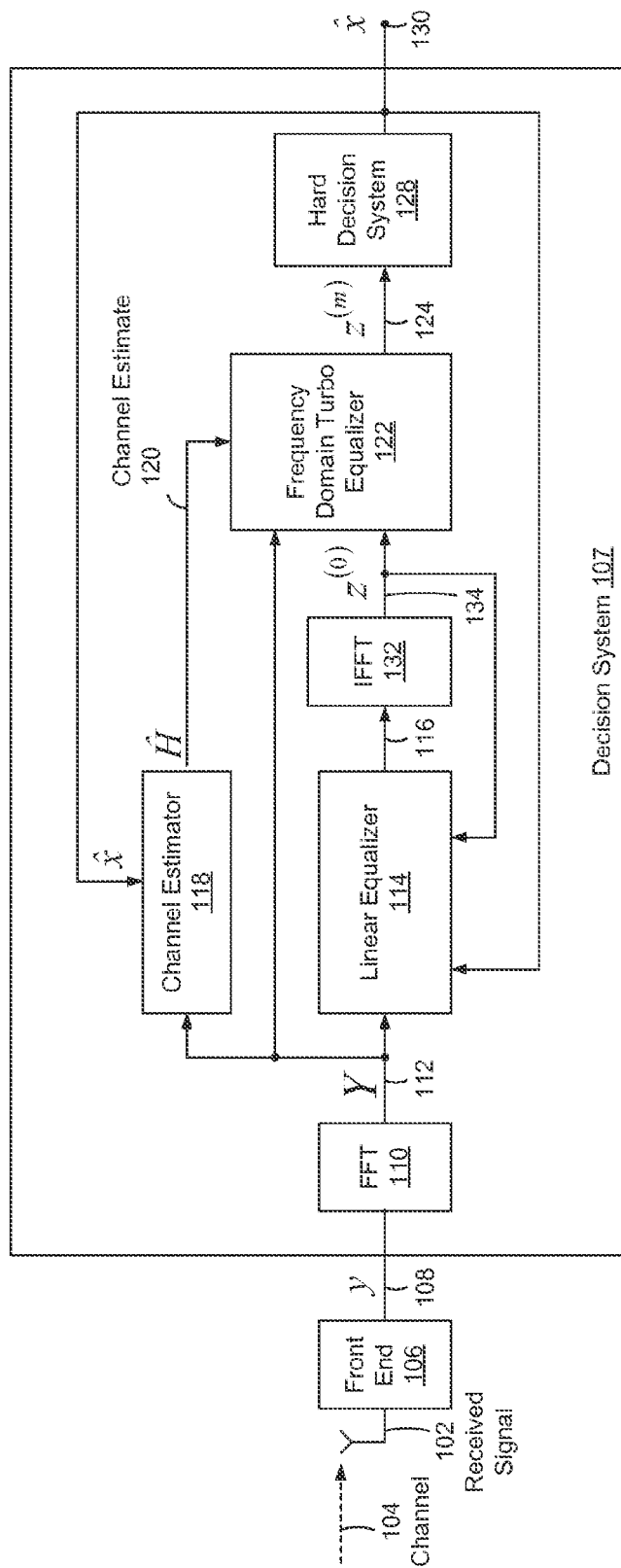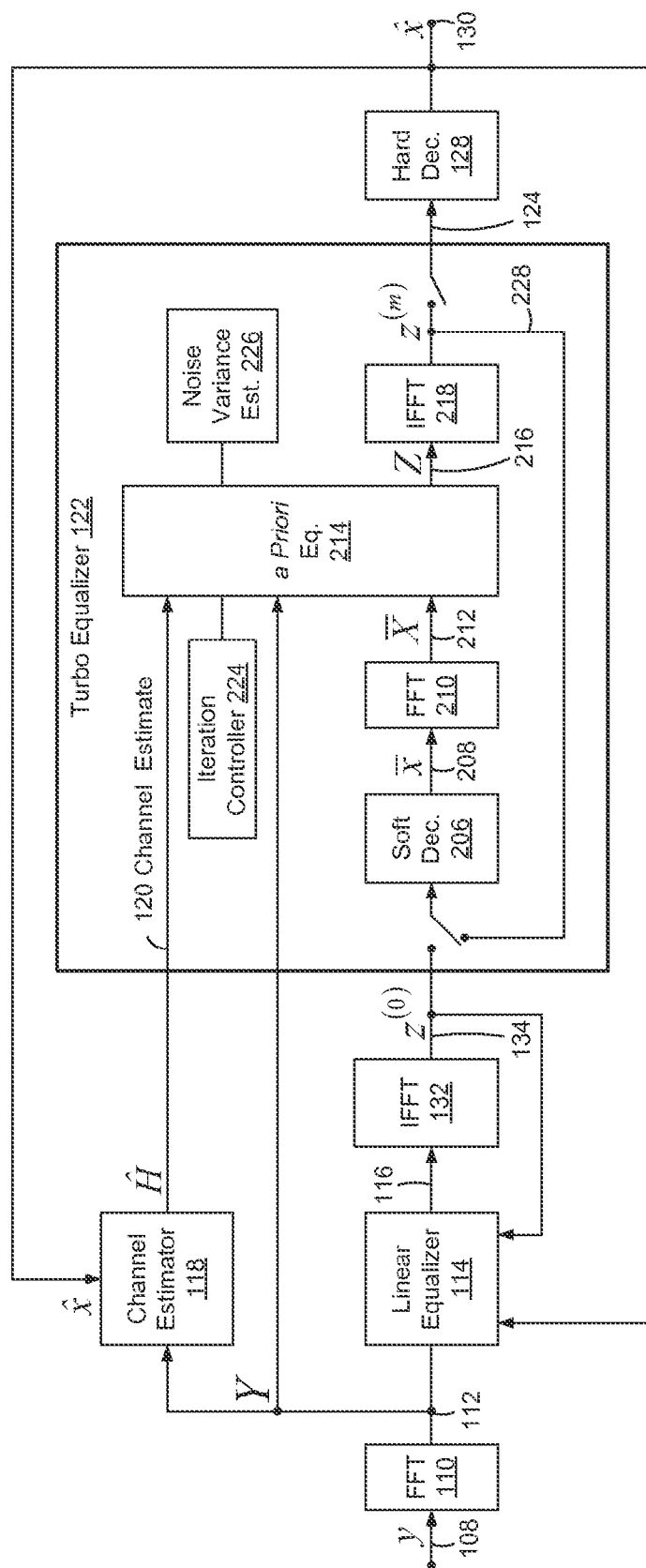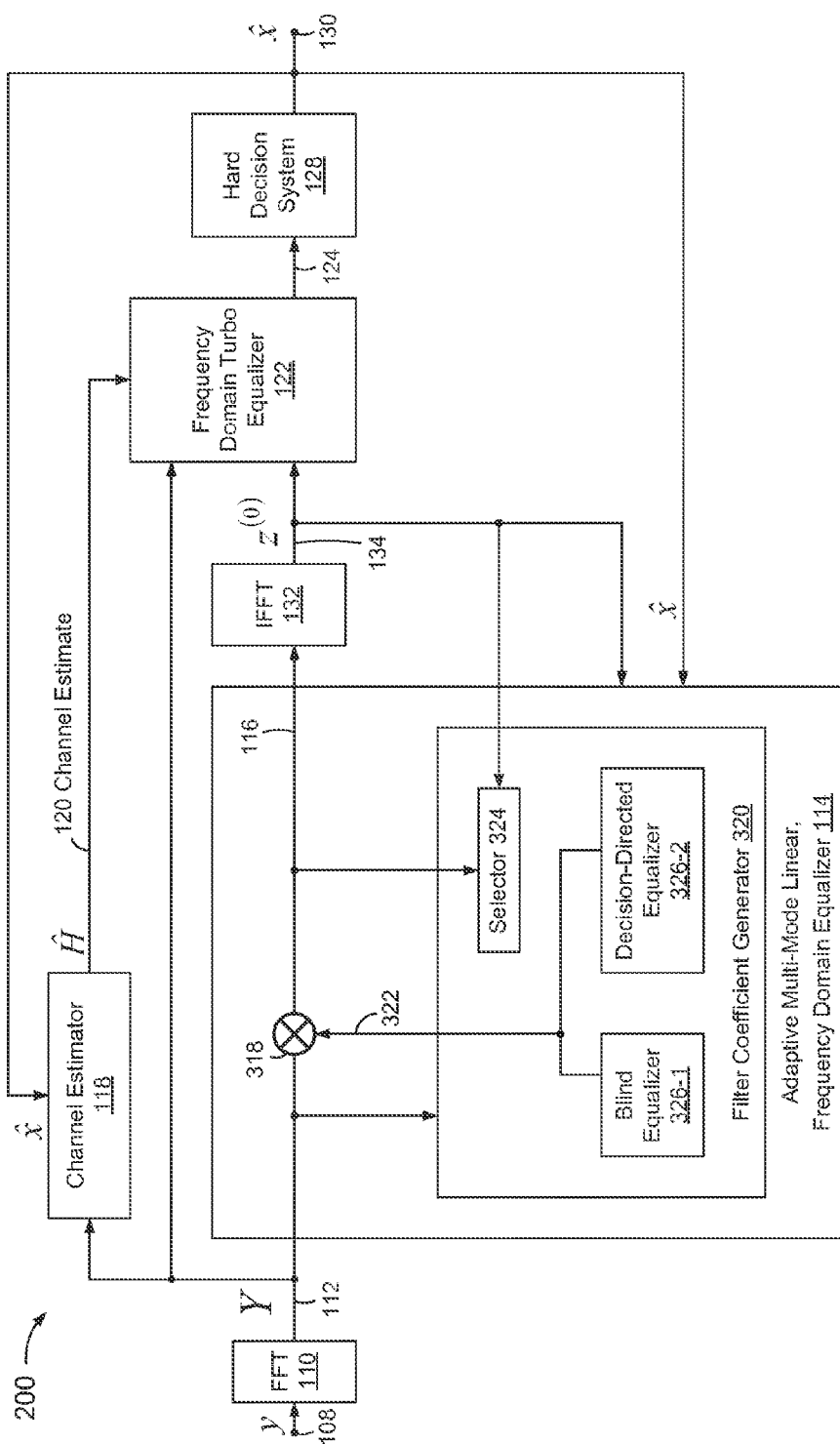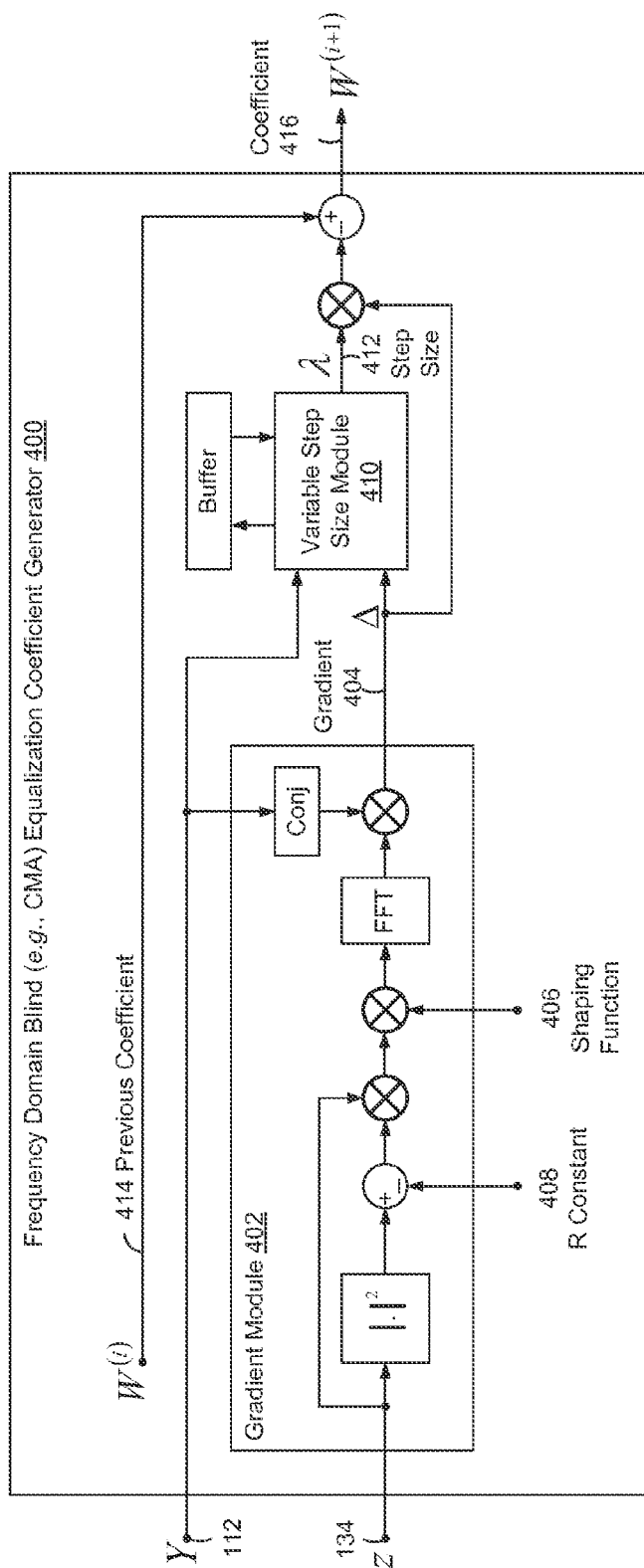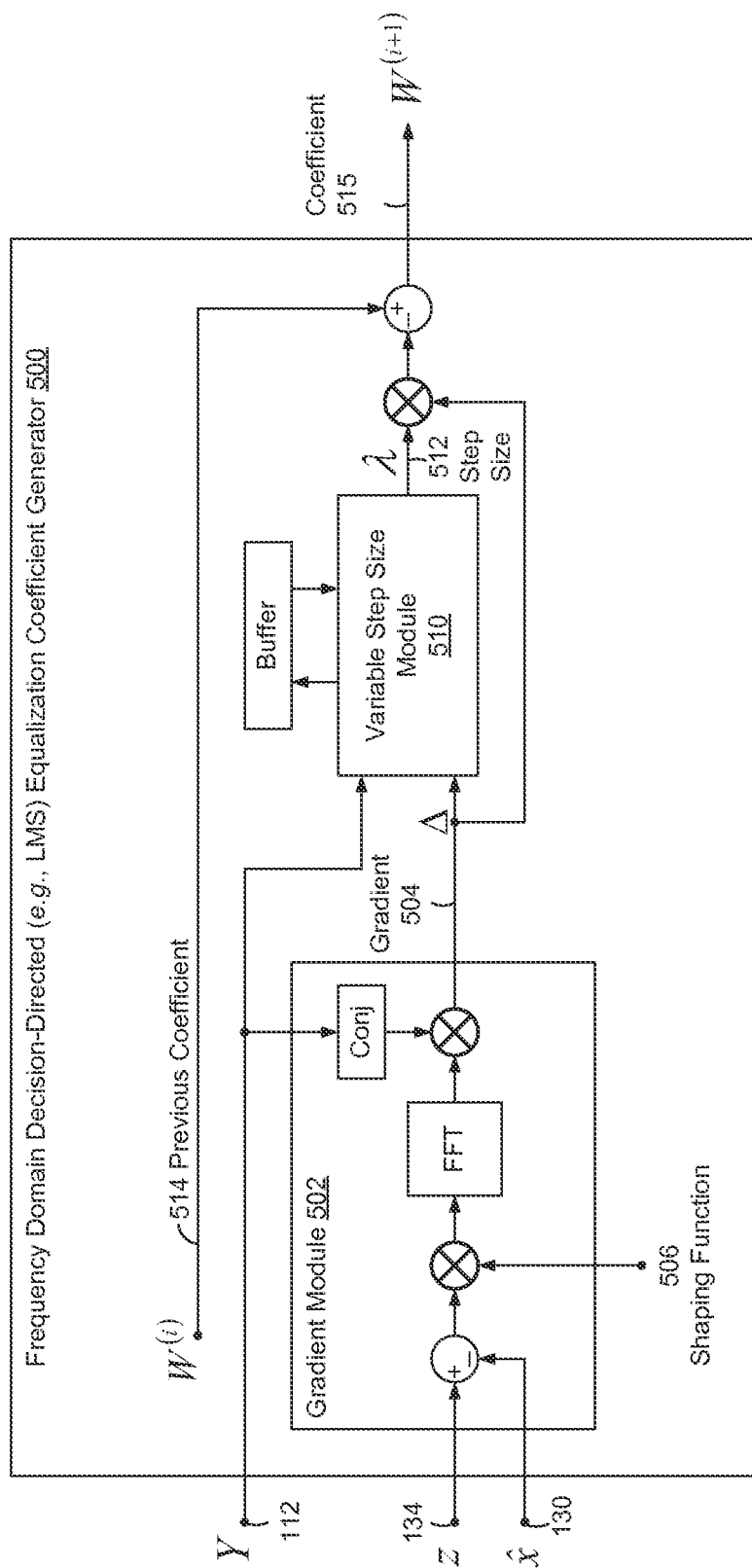
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FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5
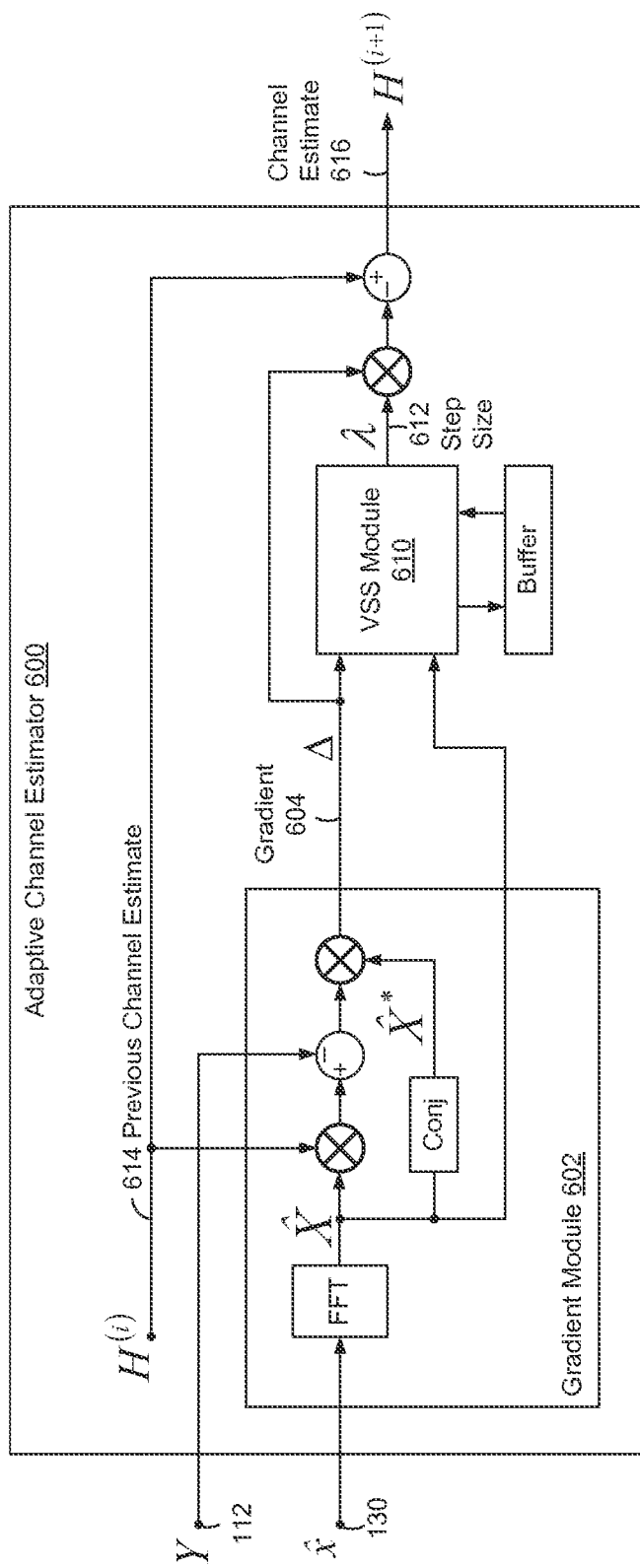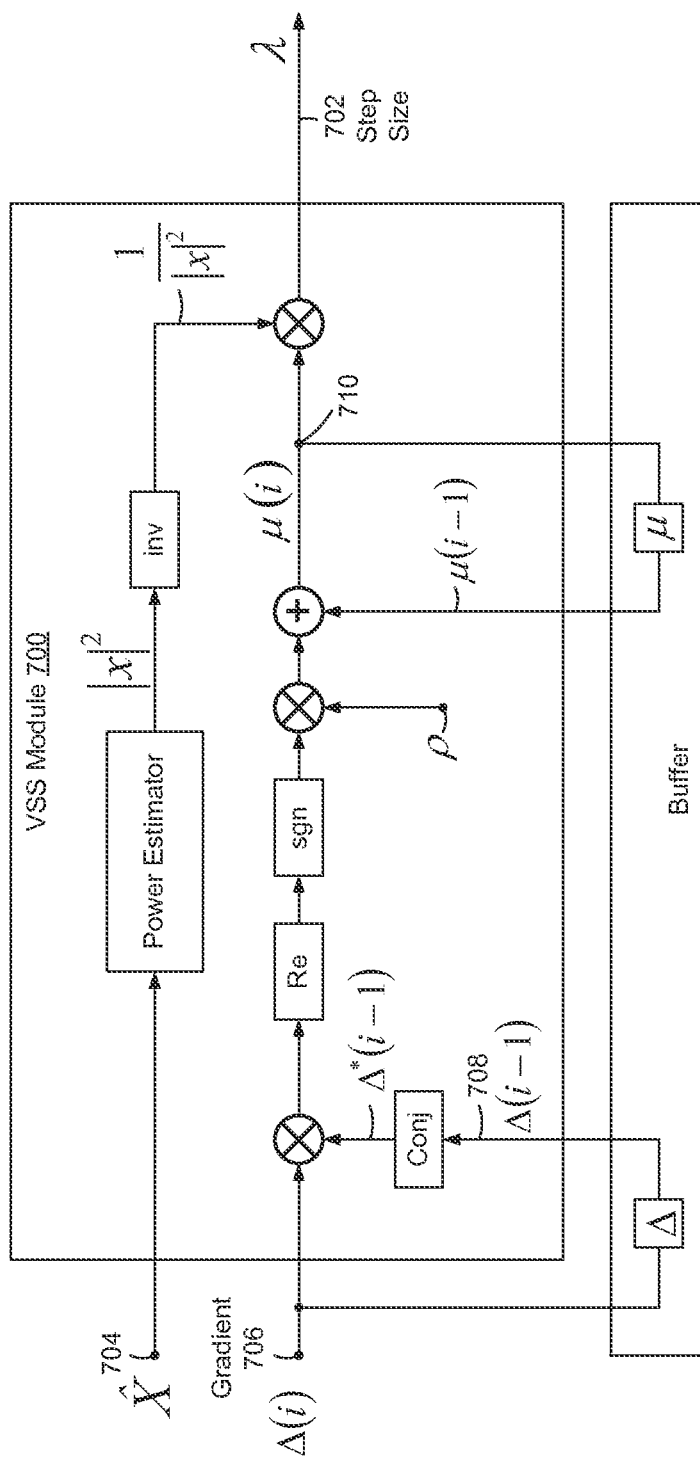
FIG. 6

FIG. 7

FIG. 8

900 ⟶

902
Convert Time Domain Samples of a Single-Carrier Signal Received over a Channel to a Frequency Domain Representation

904
Equalize the Frequency Domain Representation with a Linear Filter and Adaptive Filter Coefficients

906
Estimate Channel Frequency Response with Adaptive Decision-Directed Technique

908
Turbo Equalize the Frequency Domain Representation of the Received Signal

910
Generate Hard Decisions Regarding Symbols of the Received Signal

FIG. 9

1000 ⟶

1002
Convert Time Domain Samples of a Single-Carrier Signal Received over a Channel to a Frequency Domain Representation

1004
Equalize the Frequency Domain Representation with an Adaptive Blind Linear Equalization Technique

1010
Estimate Channel Frequency Response with Adaptive Decision-Directed Technique

1006
MSE < Threshold?   No

1008   Yes
Equalize the Frequency Domain Representation with an Adaptive Decision-Directed Linear Equalization Technique

1012
Turbo Equalize the Frequency Domain Representation of the Received Signal

1014
Generate Hard Decisions Regarding Symbols of the Received Signal

FIG. 10

1100 —

1102
Convert Time Domain Samples of a Single-Carrier Signal Received over a Channel to a Frequency Domain Representation

1104
Equalize the Frequency Domain Representation with a Linear Filter and Adaptive Filter Coefficients

1106
Estimate Channel Frequency Response with Adaptive Decision-Directed Technique

1108
Adaptively Estimate Noise Variance

1110
Turbo Equalize the Frequency Domain Representation of the Received Signal

1112
No   MSE < Threshold?

1114
Max. No. Iterations?   No

1116   Yes
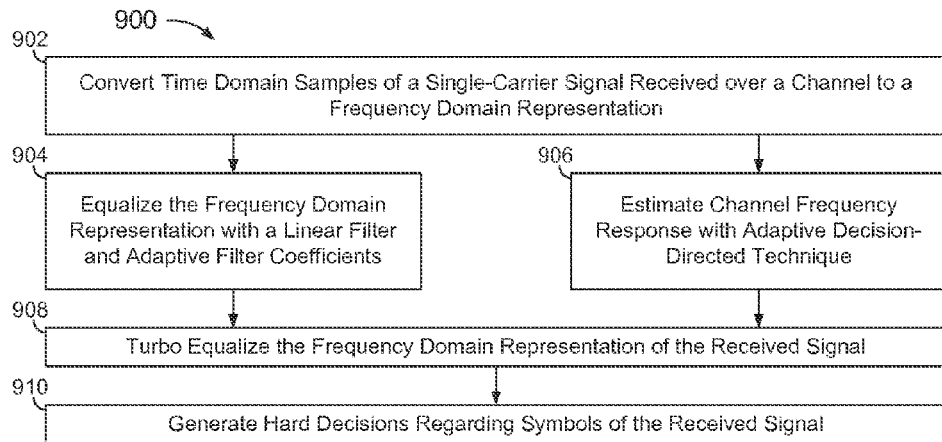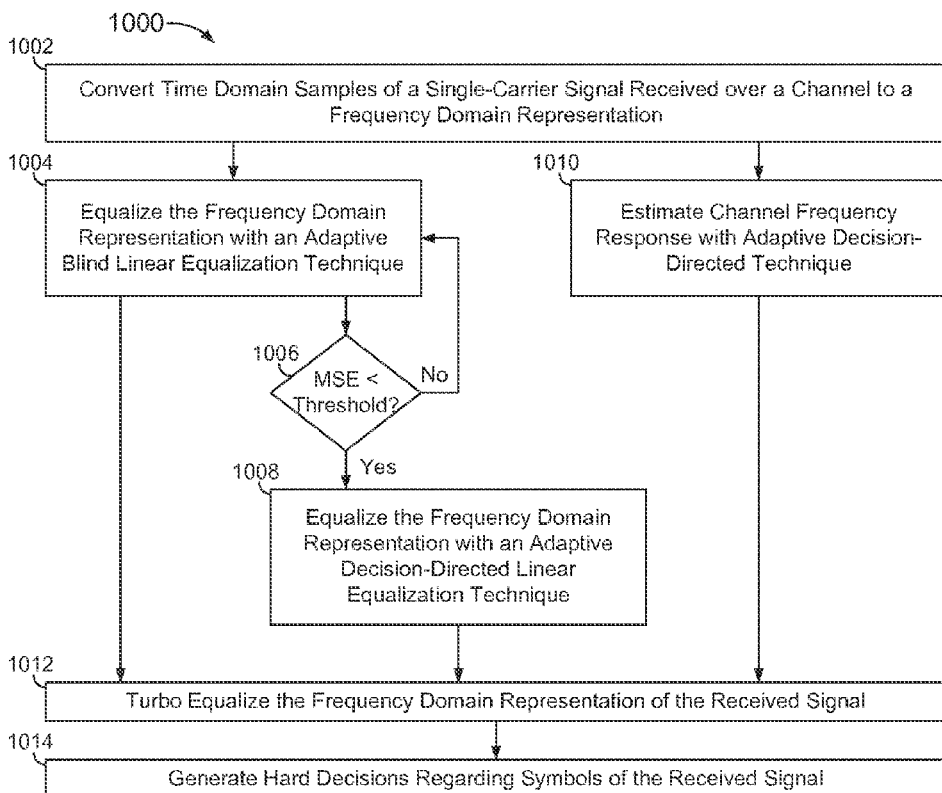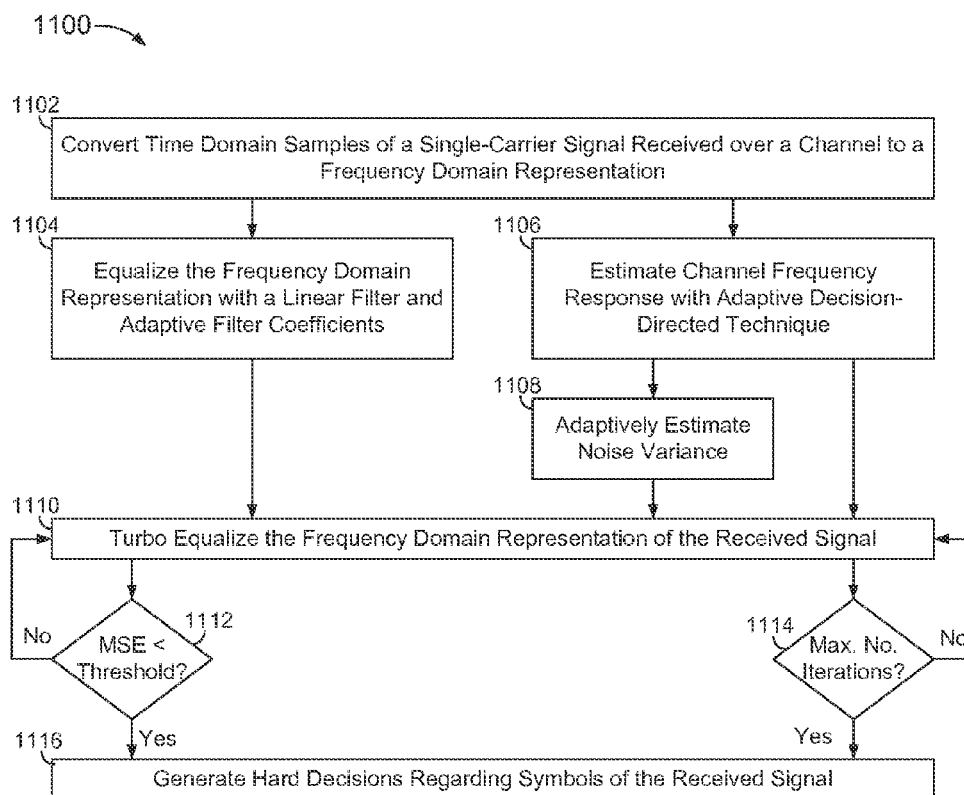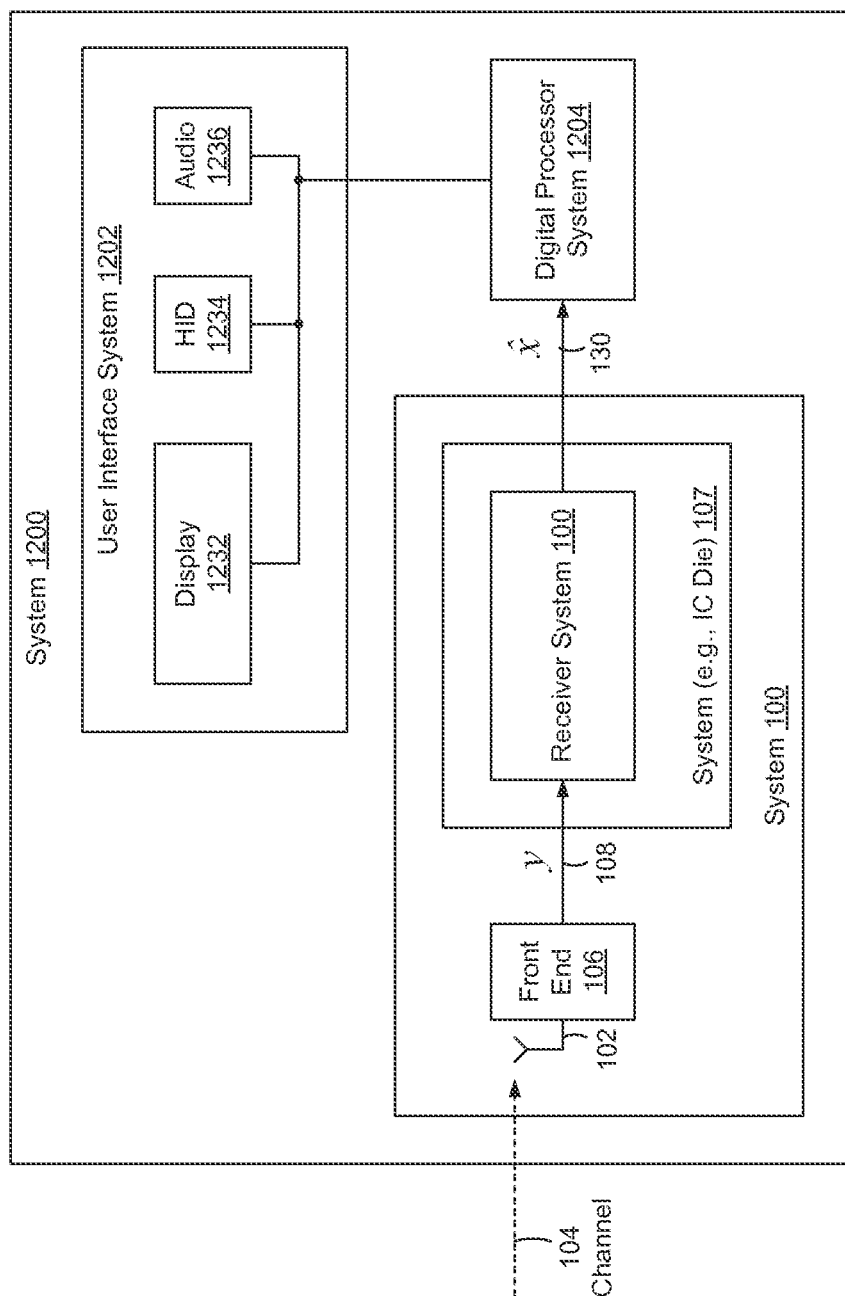Generate Hard Decisions Regarding Symbols of the Received Signal

Yes

FIG. 11

FIG. 12

FREQUENCY-DOMAIN TURBO EQUALIZATION, INCLUDING MULTI-MODE ADAPTIVE LINEAR EQUALIZATION, ADAPTIVE DECISION-DIRECTED CHANNEL ESTIMATION, ADAPTIVE NOISE VARIANCE ESTIMATION, AND DYNAMIC ITERATION CONTROL

BACKGROUND

Conventional single-carrier communication systems, such as digital television (DTV) receivers, use time-domain decision feedback equalizers (DFE) to compensate for signal distortions caused by inter-symbol interference in a wireless channel.

Time-domain decision feedback equalizers are relatively complex, and become more complex for a channel having a relatively long impulse response, as may be encountered with DTV wireless channels.

A frequency domain equalizer may be implemented with less complexity than a time domain DFE.

Where a received signal lacks a cyclic prefix, iterative or turbo equalization may be utilized to achieve a more-satisfactory error rate.

A conventional turbo equalizer may use a pre-defined number of iterations in the equalization of each input block. At low signal-to-noise ratio (SNR), too much iteration may decrease equalizer error rate. At high SNR, too much iteration may cause numerical instability.

BRIEF DESCRIPTION OF THE DRAWINGS/FIGURES

FIG. 1 is a block diagram of a system to perform one or more of adaptive multi-mode pre-decoding linear equalization, adaptive channel estimation, turbo equalization, turbo equalization iteration control, and noise variance estimation, one or more of which may be performed in the frequency domain.

FIG. 2 is a block diagram of an example implementation of a frequency domain based turbo equalizer, including an adaptive noise variance estimator and dynamic iteration control.

FIG. 3 is a block diagram of a receiver system including an example implementation of an adaptive multi-mode frequency domain linear equalizer.

FIG. 4 is a block diagram of a frequency domain based constant modulus algorithm (CMA) equalizer coefficient generator (CMA module).

FIG. 5 is a block diagram of a frequency domain based least means squared (LMS) equalizer coefficient generator (LMS module).

FIG. 6 is a block diagram of an adaptive decision-directed channel estimator.

FIG. 7 is a block diagram of a variable step size (VSS) module to generate a VSS for one or more of the CMA module of FIG. 4, the LMS module of FIG. 5, and the channel estimator of FIG. 6.

FIG. 8 is a block diagram of an adaptive noise variance estimator to estimate noise variance for turbo equalization.

FIG. 9 is a flowchart of a method of estimating symbols of a received signal in the frequency domain.

FIG. 10 is a flowchart of a method of estimating symbols of a received signal in the frequency domain, including adaptively linearly equalizing a frequency domain representation of the received signal based on one or more of multiple selectable equalization techniques.

FIG. 11 is a flowchart of a method of estimating symbols of a received signal in the frequency domain based in part on an adaptively estimated noise variance and dynamic turbo equalization termination criteria.

FIG. 12 is a block diagram of a system, including the system of FIG. 1, a user interface system, and a digital processor system.

In the drawings, the leftmost digit(s) of a reference number identifies the drawing in which the reference number first appears.

DETAILED DESCRIPTION

FIG. 1 is a block diagram of a system 100 to receive a signal 102 over a channel 104.

Signal 102 may represent a single-carrier signal, such as a digital television broadcast signal, which may be formatted in accordance with a digital television (DTV) standard promulgated by the Advanced Television Systems Committee (ATSC), based in Washington, D.C. System 100 is not, however, limited to these examples.

Channel 104 which may include a wireless channel, characteristics of which may impact symbols of signal 102, such as to rotate constellations of the symbols.

System 100 may include a front end system 106 to frequency down-convert and sample signal 102. System 100 may further include a decision system 107 to evaluate signal 102 and estimate symbols of signal 102 based on the evaluation.

Decision system 107 may be implemented to perform one or more of adaptive multi-mode pre-decoding linear equalization, adaptive channel estimation, turbo equalization, turbo equalization iteration control, and noise variance estimation, one or more of which may be performed in the frequency domain.

Decision system 107 may include a fast Fourier transform (FFT) module 110 to transform time domain samples 108 of signal 102 to a frequency domain representation or frequency tones Y 112.

Decision system 107 may include a linear equalizer 114 to equalize frequency tones 112. Linear equalizer 114 may be implemented as a multi-mode adaptive linear equalizer to equalize frequency domain tones 112 based one or more of multiple selectable equalization techniques.

Decision system 107 may include an inverse fast Fourier transform (IFFT) module 132 to transform equalized frequency tones 116 to time domain bits or samples 134, also referred to herein as a time domain output of linear equalizer 114.

Decision system 107 may include a channel estimator 118 to generate a channel estimate 120, such as a channel frequency response and/or a channel impulse response.

Channel estimator 118 may be implemented to generate channel estimate 120 from pilots or pilot signals of signal 102.

Alternatively, or additionally, channel estimator 118 may include an adaptive decision-directed channel estimator to generate channel estimate 120 based on prior decisions and an adaptive variable step size (VSS) algorithm. An adaptive decision-directed channel estimator may be useful for a relatively long channel response where a pilot sequence may be too short to estimate the channel, and/or for a time-varying channel response where an interval between pilot sequences may be too long to estimate the channel.

Decision system 107 may include a frequency domain turbo equalizer 122 to generate estimated symbol decisions

124 from frequency domain tones 112 based on time domain output 134 of linear equalizer 114, channel estimate 120, and prior decisions.

Decision system 107 may include a hard decision system 128 to generate hard decisions 130 regarding symbols of signal 102. Hard decision system 128 may include, for example, a Viterbi decoder.

Decision system 107, or portions thereof, may be implemented as described in one or more examples below.

FIG. 2 is a block diagram of an example implementation of turbo equalizer 122 including an adaptive noise variance estimator 226 and an iteration controller 224. Methods and systems disclosed herein are not limited to the example of FIG. 2.

Turbo equalizer 122 further includes a soft decision module 206 to generate soft decisions 208. Soft decisions 208 may include estimated bit values and corresponding probabilities of correctness.

Soft decision module 206 may include a Maximum a Posteriori (MAP) decoder to provide a set of posterior probabilities for a symbol of signal 102 based on a time-domain output $z^{(0)}$ 134 of linear equalizer 114 or results $z^{(m)}$ 228 of prior iterations.

A set of posterior probabilities may be represented as:

$$\{p(x_i=s|z)\}_{s \in S} \qquad \text{EQ. (1)}$$

A soft decision 208 may be represented as:

$$\hat{x}_i = \sum_s s \cdot p(x_i = s \mid z) \qquad \text{EQ. (2)}$$

An estimated mean square error (MSE) of a soft decision 208 may be computed as in EQ. (3). An average MSE may be computed as in EQ. (4).

$$v_i = \sum_s (s - \hat{x}_i)^2 \cdot p(x_i = s \mid z) \qquad \text{EQ. (3)}$$

$$\bar{v} = \frac{1}{N} \sum_{i=0}^{N-1} v_i \qquad \text{EQ. (4)}$$

Turbo equalizer 122 may further include an FFT module 210 to transform soft decisions $\bar{x}$ 208 to a frequency domain representation or frequency domain elements 212.

Turbo equalizer 122 may further include an equalizer 214 to transform frequency domain tones Y 112 to blocks of frequency domain elements 216 corresponding to estimated symbols of signal 102 (FIG. 1). Equalizer 214 may be implemented to determine elements 216 based on soft-decision frequency domain elements $\bar{X}$ 212, channel estimate 120, and a priori information derived from prior decisions. A priori information may be provided directly to equalizer 214 and/or indirectly through one or more of soft decisions module 206, linear equalizer 114, and/or channel estimator 118, such as described in one or more examples below.

For disambiguation purposes, equalizer 214 may be referred to as an a priori equalizer, and linear equalizer 114 may be referred to as a pre-decoder equalizer.

Equalizer 214 may be implemented to determine elements Z_k of a frequency domain output block Z 216 as:

$$Z_k = \bar{X}_k + W_k(Y_k - \hat{H}_k \bar{X}_k), \forall k = 0 \dots N-1 \qquad \text{EQ. (5)}$$

$$W_k = \frac{\hat{H}_k^*}{|\hat{H}_k|^2 + \frac{\sigma^2}{v}}, \qquad \text{EQ. (6)}$$

In EQS. (5) and (6):

k=0, 1, 2, . . . N−1;

N denotes a size or number of output frequency bins or tones of FFT module 210, which may correspond to a number of subcarriers of Y 112;

Y denotes channel output 112 in the frequency domain;

X denotes Fourier transform 212 of soft decisions 208;

H denotes channel estimate 120;

σ^2 denotes a noise variance;

$\bar{v}$ denotes an average MSE of soft decisions 208; and

W denotes filter coefficients or weights of a priori equalizer 214.

Turbo equalizer 122 may include noise variance estimator 226 to determine noise variance σ^2 such as described further below with reference to FIG. 8.

Turbo equalizer 122 may further include an IFFF module 218 to transform blocks of frequency domain elements 216 to time domain decision blocks 124.

Termination Criteria

Soft decision system 206 and a priori equalizer 214 may be implemented to iteratively process blocks of time domain samples 204 and preliminary decisions 228 for each symbol of signal 102.

Turbo equalizer 122 may be implemented to perform a pre-defined and/or fixed number of iterations for each block or symbol before outputting a final decision estimate z 124.

Alternatively, turbo equalizer 122 may include iteration controller 224 to dynamically control a number of turbo equalization iterations performed with respect to a each block or symbol.

A dynamic termination criterion may include a noise-based threshold, which may be based on the average MSE of soft decisions 208. Turbo equalization iterations may be halted, for example, when MSE $\bar{v}$ is below a threshold value. This may serve to increase the number of iterations at a relatively low SNR, which may decrease an equalization error rate. This may also serve to reduce the number of iterations at a relatively high SNR, which may improve numerical stability.

A dynamic termination criterion may be combined with other one or more additional termination criteria, which may be dynamic or static. For example, a maximum number of iterations per block or per symbol may be defined, which may reduce equalizer complexity.

Adaptive Linear Frequency Domain Pre-Decode Equalization

FIG. 3 is a block diagram of a receiver system 300, including an example implementation of linear equalizer 114. Methods and systems disclosed herein are not limited to the example of FIG. 3.

In FIG. 3, linear equalizer 114 is illustrated as an adaptive multi-mode linear frequency domain equalizer 114 to equalize frequency domain tones Y 112 based on one or more of multiple selectable equalization techniques.

Linear equalizer 114 may include a frequency domain filter 318 to filter frequency domain elements Y 112, and may further include a filter coefficient generator 320 to generate filter coefficients or weights 322.

Coefficient generator **320** may be implemented to compute coefficients **322** based on one or more linear frequency domain equalization techniques, and to adapt coefficients **322** to time-varying properties of channel **104** in FIG. **1**.

Coefficient generator **320** may be implemented to adapt coefficients **322** based on an adaptive variable step size (VSS) algorithm. Step size may be varied to control a rate of convergence, and may represent an estimated subcarrier step size.

Coefficient generator **320** may be implemented to compute coefficients **322** based on one or more blind equalization techniques and/or decision-directed techniques such as described in examples below. Coefficient generator **320** is not, however, limited to the examples herein.

Filter coefficient generator **320** may include multiple equalizer modules **326**, each to generate filter coefficients **322** based on a corresponding equalization technique.

As an example, filter coefficient generator **320** may include a blind equalizer module **320-1** and a decision-directed equalizer module **320-2**.

Blind equalizer module **320-1** may be implemented to adjust filter coefficients **322** to minimize a cost function, which may be based on known or determinable signal statistics, such as a mean energy, and may be implemented to determine filter coefficients **322** without pilot signals or other channel-specific information or statistics.

Blind equalization may be viewed as estimating an equalization filter corresponding to an inverse of a channel impulse response, rather than an estimation of the channel impulse response, and convolving the estimated filter with a received signal to yield an estimation of a corresponding transmitted signal.

Blind equalizer module **320-1** may be implemented based on, for example, a constant modulus (i.e., higher-order statistics) algorithm (CMA), a Sato algorithm, and/or a multimodulus algorithm (MMA). An example CMA based equalization coefficient generator is described below with reference to FIG. **4**.

Decision-directed equalizer module **320-2** may be implemented based on a least means squared (LMS) technique to adapt coefficients **322** to reduce mean squares of an error at output **116**. An LMS technique may be viewed as a stochastic gradient descent technique, in that filter coefficients are adapted based on an error at a present or current time.

An example LMS equalization coefficient generator is described below with reference to FIG. **5**.

Filter coefficient generator **320** may include a selector **324** to select one of multiple equalizer modules **326** to generate filter coefficients **322** based on one or more criteria.

For example, a conventional LMS equalizer may initially use pilot data to adjust equalizer weights. Thereafter, the LMS equalizer may use decoder decisions to track time varying channels. Where initial pilot data is missed or too short, the output of the LMS equalizer may not be correctly decoded. This may impede the LMS equalizer from converging on a set of filter weights.

A blind coefficient generator may operate without pilot-based adjustments, while a decision-directed coefficient generator may provide a lower output error.

Selector **324** may be implemented to use blind equalizer **326-1** to generate initial filter coefficients or weights, and decision-directed equalizer **326-2** to refine the initial filter coefficients. In this way, decision-directed equalizer **326-2** may provide a relatively low output error without pilot signals.

Selector **324** may be implemented, for example, to select blind equalizer module **320-1** when the MSE of time domain

output **134** of linear equalizer **114** is above a threshold, and to select decision-directed equalizer module **320-2** when the MSE is below the threshold. The MSE of time domain output **134** of linear equalizer **114** may be computed using known pilot symbols.

FIG. **4** is a block diagram of a frequency domain CMA equalizer coefficient generator (CMA module) **400**, which may be implemented as blind equalizer module **326-1** in FIG. **3**.

CMA module **400** includes a gradient module **402** to generate a gradient Δ **404** based on a time domain output z **134** of linear equalizer **114**, frequency domain tones Y **112**, a shaping function **406**, and a constant **408**.

CMA module **400** further includes a VSS module **410** to estimate a step size λ **412** based on frequency domain tones Y **112** and gradient Δ **404**.

CMA module **400** may be implemented to generate a filter coefficient $W^{(i+1)}$ **416** based on a previous filter coefficient $W^{(i)}$ **414**, step size λ **412**, and gradient Δ **404** as:

$$W^{(i+1)} = W^{(i)} - (\lambda^* \Delta) \qquad \text{EQ. (9)}$$

Coefficients **414** and **416** may correspond to coefficients **322** in FIG. **3**.

FIG. **5** is a block diagram of a frequency domain LMS equalizer coefficient generator (LMS module) **500**, which may be implemented as decision-directed equalizer module **326-2** in FIG. **3**.

LMS module **500** includes a gradient module **502** to generate a frequency domain gradient Δ **504** based on a time domain output z **134** of linear equalizer **114**, hard decisions $\hat{x}$ **130**, frequency domain tones Y **112**, and a shaping function **506**.

LMS module **500** further includes a variable step size (VSS) module **510** to estimate a step size λ **512** based on frequency domain tones Y **112** and gradient Δ **504**.

LMS module **500** may be implemented to generate a filter coefficient $W^{(i+1)}$ **516** based on a previous filter coefficient $W^{(i)}$ **514**, step size λ **512** and gradient Δ **504** in accordance with EQ. (9) above.

Coefficients **514** and **516** may correspond to coefficients **322** in FIG. **3**.

Adaptive Channel Estimation

As illustrated in EQS. (5) and (6), channel estimate $\hat{H}$ **120** may need to be determined prior to generating a decision estimate **124**. In addition, and as described above, channel estimate **120** may need to be determined without reliance on pilot signals.

FIG. **6** is a block diagram of an adaptive decision-directed channel estimator **600** to generate channel estimates $H^{(i+1)}$ **616** without pilot signals. Channel estimates $H^{(i+1)}$ **616** may correspond to channel estimates **120** in FIG. **1** and/or FIG. **2**.

Channel estimator **600** includes a gradient module **602** to generate a gradient Δ **604** based on a previous channel estimate $H^{(i)}$ **614**, frequency domain tones Y **112**, and a frequency domain transform of a hard decision $\hat{x}$ **130**.

Channel estimator **600** further includes a VSS module **610** to estimate a step size λ **612** based on gradient Δ **604** and the frequency domain transform of hard decision $\hat{x}$ **130**.

Channel estimator **600** may be implemented to generate channel estimate $H^{(i+1)}$ **616** based on previous channel estimate $H^{(i)}$ **614**, gradient Δ **604**, and step size λ **612**, in accordance with EQ. (8).

$$\hat{H}_k(t+1) = \hat{H}_k(t) - \lambda_k (\hat{X}_k \hat{H}_k(t) - Y_k) \hat{X}_k \qquad \text{EQ. (10)}$$

In EQ. (10):

$H^{(i)}$ represents a channel estimate for a previous block;

$H^{(i+1)}$ represents a channel estimate for a current block; and

λ_k represents a step size for the current block.

Variable Step Size Determination

In FIGS. **4**, **5**, and **6**, VSS modules **410**, **510**, and **610** may be implemented similar to one another, and may represent a shared VSS module. VSS modules **410**, **510**, and/or **610** may be implemented with one or more conventional VSS techniques, or as described below with reference to FIG. **7**.

FIG. **7** is a block diagram of a VSS module **700** to generate an estimated step size **702** as a function of a frequency domain transform $\hat{X}$ **704** of a hard decision $\hat{x}$ **130**, a previous value of the gradient, $\Delta(i-1)$ **708**, a factor ρ, and a previous state of an internal node μ **710**, illustrated here as μ(i−1). Factor ρ represents a smoothing factor that determines a convergence rate, where 0≤ρ≤1.

Estimated step size **702** may correspond to one or more of estimated step sizes **412**, **512**, and **612** in corresponding FIGS. **4**, **5**, and **6**.

Similarly, gradient **706** may correspond one or more of gradients **404**, **504**, and **604** in corresponding FIGS. **4**, **5**, and **6**.

Adaptive Noise Variance Estimation

FIG. **8** is a block diagram of an adaptive noise variance estimator **800** to estimate noise variance σ^2. Adaptive noise variance estimator **800** may be implemented as noise variance estimator **226** in FIG. **2**.

Noise variance estimator **800** may be implemented to compute a noise variance $\hat{\sigma}^2{}_{block}$ **802** for a block undergoing turbo equalization as a function of a channel estimate $H^{(i)}$ **120**, a frequency domain transform $\hat{X}$ of a hard decision $\hat{x}$ **130**, and frequency domain tones Y **112**, in accordance with EQ. (11):

$$\hat{\sigma}_{block}^2 = \frac{1}{N} \sum_{k=0}^{N-1} \left| Y_k - \hat{H}_k(t+1)\hat{X}_k \right|^2 \qquad \text{EQ. (11)}$$

Adaptive noise variance estimator **800** may be further implemented to maintain a moving average **804** of the estimated noise variance as:

$$\hat{\sigma}^2 = \hat{\sigma}^2 \beta + (1-\beta)\hat{\sigma}_{block}{}^2 \qquad \text{EQ. (12)}$$

In EQ. (10), β is smoothing factor, also referred to herein as a forgetting factor, where 0≤β≤1.

FIG. **9** is a flowchart of a method **900** of estimating symbols of a received signal in the frequency domain.

At **902**, samples of a received single-carrier signal are converted to a frequency domain representation.

At **904**, the frequency domain representation of the signal is equalized with a linear filter and adaptive filter coefficients. The equalization at **904** may include selectively equalizing with one of multiple equalization techniques, such as described in one or more examples above.

At **906**, a frequency response is estimated for a channel of the received signal using an adaptive decision-directed technique, such as described above with reference to FIG. **6**.

At **908**, the frequency domain representation of the signal is turbo equalized based on results of the linear equalization at **904** and the estimated channel response.

At **910**, hard decisions are generated regarding symbols of the received signal.

FIG. **10** is a flowchart of a method **1000** of estimating symbols of a received signal in the frequency domain, including adaptively linearly equalizing the frequency domain rep-

resentation of the received signal based on one or more of multiple selectable techniques.

At **1002**, samples of a received single-carrier signal are converted to a frequency domain representation.

At **1004**, the frequency domain representation of the signal is equalized with an adaptive blind equalization technique, such as a CMA technique.

At **1006**, where the MSE of results of the equalization at **904** are below a threshold, processing may proceed to **1008** where the frequency domain representation of the signal is equalized with an adaptive decision-directed equalization technique, such as a LMS technique.

At **1010**, a frequency response is estimated for a channel of the received signal using an adaptive decision-directed technique.

At **1012**, the frequency domain representation of the signal is turbo equalized based on results of the linear equalization at **1004** and/or **1008**, and the estimated channel response.

At **1014**, hard decisions are generated regarding symbols of the received signal.

FIG. **11** is a flowchart of a method **1100** of estimating symbols of a received signal in the frequency domain based in part on an adaptively estimated a noise variance and dynamic turbo equalization termination criteria.

At **1102**, samples of a received single-carrier signal are converted to a frequency domain representation.

At **1104**, the frequency domain representation of the signal is equalized with a linear filter and adaptive filter coefficients such as described above with respect to **904** and/or **1004** through **1008**.

At **1106**, a frequency response is estimated for a channel of the received signal using an adaptive decision-directed technique.

At **1108**, a noise variance is estimated, such as described above with reference to FIG. **8**.

At **1110**, the frequency domain representation of the signal is turbo equalized based on results of the linear equalization at **1104**, the estimated channel response, and the estimated noise variance, such as described above with reference to EQS. (5) and (6).

At **1112**, an MSE of a soft decoder output may be compared to a threshold. When the MSE is below the threshold, turbo equalization iteration may be halted and a decision estimate for a symbol may be output for hard decision processing at **1116**.

At **1114**, the number of iterations of a block being turbo equalized may be compared to a maximum iteration threshold. Where the maximum iteration threshold is reached, turbo equalization iteration may be halted and a decision estimate for a symbol may be output for hard decision processing at **1116**.

One or more of methods **900**, **1000**, and **1100** may include computing variable step sizes for one or more adaptive linear frequency domain equalization techniques and/or channel estimation, such as described in one or more examples above.

Methods and systems disclosed herein may be implemented in hardware, software, firmware, and combinations thereof, including discrete and integrated circuit logic, application specific integrated circuit (ASIC) logic, and microcontrollers, and may be implemented as part of a domain-specific integrated circuit package, and/or a combination of integrated circuit packages. Software may include a computer readable medium encoded with a computer program including instructions to cause a processor to perform one or more functions in response thereto. The computer readable medium may include a transitory and/or non-transitory medium. The pro-

cessor may include a general purpose instruction processor, a controller, a microcontroller, and/or other instruction-based processor.

Methods and systems disclosed herein may be implemented with respect to one or more of a variety of systems including one or more consumer systems, such as described below with reference to FIG. **12**. Methods and systems disclosed herein are not, however, limited to the example of FIG. **12**.

FIG. **12** is a block diagram of a system **1200** including system **100** of FIG. **1**, a user interface system **1202**, and a digital processor system **1204** to process hard decisions **130** and output corresponding information to user interface system **1202**. In FIG. **12**, system **100** or portions thereof may be implemented as described with respect to one or more of examples herein.

System **100**, digital processor system **1204**, and/or portions thereof, may be implemented within one or more integrated circuit dies, and may be implemented as a system-on-a-chip (SoC).

User interface system **1202** may include a monitor or display **1232** to display information from digital processor system **1230**.

User interface system **1202** may include a human interface device (HID) **1234** to provide user input to digital processor system **1230**. HID **1234** may include, for example and without limitation, one or more of a key board, a cursor device, a touch-sensitive device, and or a motion and/or image sensor. HID **1234** may include a physical device and/or a virtual device, such as a monitor-displayed or virtual keyboard.

User interface system **1202** may include an audio system **1236** to receive and/or output audible sound.

System **1200** may further include a transmitter system to transmit signals from system **1200**.

System **1200** may correspond to, for example, a computer system, a personal communication device, and/or a television set-top box.

System **1200** may include a housing to receive one or more of system **100**, digital processor system **1204**, user interface system **1202**, or portions thereof. The housing may include, without limitation, a rack-mountable housing, a desk-top housing, a lap-top housing, a notebook housing, a net-book housing, a set-top box housing, a portable housing, and/or other conventional electronic housing and/or future-developed housing. For example, system **100** may be implemented to receive a digital television broadcast signal, and system **1200** may include a set-top box housing or a portable housing, such as a mobile telephone housing.

Methods and systems are disclosed herein with the aid of functional building blocks illustrating functions, features, and relationships thereof. At least some of the boundaries of these functional building blocks have been arbitrarily defined herein for the convenience of the description. Alternate boundaries may be defined so long as the specified functions and relationships thereof are appropriately performed.

While various embodiments are disclosed herein, it should be understood that they have been presented by way of example only, and not limitation. It will be apparent to persons skilled in the relevant art that various changes in form and detail may be made therein without departing from the spirit and scope of the methods and systems disclosed herein. Thus, the breadth and scope of the claims should not be limited by any of the example embodiments disclosed herein.

What is claimed is:

1. An apparatus, comprising:
an adaptive linear equalizer to equalize frequency domain samples of a single-carrier signal received over a chan-

nel, including to compute a first gradient based on the frequency domain samples of the received signal and prior decisions, compute a first variable step size based on the first gradient, and adapt filter coefficients of the adaptive linear equalizer based on the first variable step size;
an adaptive decision-directed channel estimator to estimate a characteristic of the channel in the frequency domain, including to compute a second gradient based on the frequency domain samples of the received signal and the prior decisions, compute a second variable step size based on the second gradient, and adapt a prior estimate of the characteristic of the channel based on the second gradient;
a turbo equalizer to generate estimated decisions based on prior estimated decisions, the output of the adaptive linear equalizer, and an output of the adaptive decision-directed channel estimator; and
a hard decision system to generate hard decisions based on the estimated decisions.

2. The apparatus of claim **1**, wherein the adaptive linear equalizer includes:
a multi-mode equalizer to equalize the frequency domain samples of the received signal in the frequency domain based on one or more of multiple selectable adaptive linear equalization techniques.

3. The apparatus of claim **2**, wherein the adaptive linear equalizer includes:
a linear filter;
a blind equalizer to generate initial frequency domain filter coefficients based on a blind equalization technique;
a decision-directed equalizer to refine the initial frequency domain filter coefficients; and
a selector to apply filter coefficients from one of the blind equalizer and the decision-directed equalizer based on a measure of noise in the output of the linear filter.

4. The apparatus of claim **3**, wherein the adaptive linear equalizer is configured to:
compute the first gradient based on the frequency domain samples of the received signal and an output of the adaptive linear equalizer when the filter coefficients of the blind equalizer are applied; and
compute the first gradient based on the frequency domain samples of the received signal, the output of the adaptive linear equalizer, and the hard decisions of the turbo equalizer when the filter coefficients of the decision-directed equalizer are applied.

5. The apparatus of claim **1**, wherein the turbo equalizer includes:
a soft decision system an equalizer to iteratively process blocks of data and the prior decisions; and
an iteration controller to control a number of the iterations per block based on one or more variables.

6. The apparatus of claim **5**, wherein the iteration controller is configured to halt the iterations when a mean square error (MSE) of an output of the soft decision system is below a threshold.

7. The apparatus of claim **6**, wherein the iteration controller is further configured to halt the iterations when the number of iterations with respect to a block equals a pre-defined number.

8. The apparatus of claim **1**, wherein the turbo equalizer is configured to generate the estimated decisions based further on an estimated noise variance, and where the apparatus further includes:
an adaptive noise variance estimator to estimate the noise variance in the frequency domain based on the frequency domain representation of the received signal, the

estimated channel frequency response, and a frequency domain representation of a hard decision.

9. A system, comprising:
a receiver front end to provide frequency domain samples of a single-carrier signal received over a channel;
a decision system, including,
an adaptive linear equalizer to equalize the frequency domain samples, including to compute a first gradient based on the frequency domain samples of the received signal and prior decisions, compute a first variable step size based on the first gradient, and adapt filter coefficients of the adaptive linear equalizer based on the first variable step size,
an adaptive decision-directed channel estimator to estimate a characteristic of the channel in the frequency domain, including to compute a second gradient based on the frequency domain samples of the received signal and the prior decisions, compute a second variable step size based on the second gradient, and adapt a prior estimate of the characteristic of the channel based on the second gradient,
a turbo equalizer to generate estimated decisions based on prior estimated decisions, an outputs of the adaptive linear equalizer, and an output of the adaptive decision-directed channel estimator,
a hard decision system to generate hard decisions based on the estimated decisions; and
a digital signal processor to process the hard decisions and output corresponding information to a user interface system.

10. The system of claim 9, wherein the single-carrier signal includes a digital video broadcast signal, and wherein the digital signal processor includes:
a digital video signal processor to process the hard decisions and output corresponding video and audio signals to the user interface system.

11. The system of claim 10, configured as a digital set set-top box.

12. The system of claim 10, further including a user interface, wherein the user interface includes a display, an audio system, and a human interface device to receive user input.

13. The system of claim 9, wherein the adaptive linear equalizer includes:
a multi-mode adaptive linear equalizer to equalize the frequency domain samples of the received signal in the

frequency domain based on one or more of multiple selectable adaptive linear equalization techniques.

14. The system of claim 13, wherein the adaptive linear equalizer includes:
a linear filter;
a blind equalizer to generate initial frequency domain filter coefficients based on a blind equalization technique;
a decision-directed equalizer to refine the initial frequency domain filter coefficients; and
a selector to apply filter coefficients from one of the blind equalizer and the decision-directed equalizer based on a measure of noise in the output of the linear filter.

15. The system of claim 14, wherein the adaptive linear equalizer is configured to:
compute the first gradient based on the frequency domain samples of the received signal and an output of the adaptive linear equalizer when the filter coefficients of the blind equalizer are applied; and
compute the first gradient based on the frequency domain samples of the received signal, the output of the adaptive linear equalizer, and the hard decisions of the turbo equalizer when the filter coefficients of the decision-directed equalizer are applied.

16. The system of claim 9, wherein the turbo equalizer includes:
a soft decision system and an equalizer to iteratively process blocks of data to generate the estimated decisions; and
an iteration controller to control a number of the iterations per block based on one or more variables.

17. The system of claim 16, wherein the iteration controller is configured to halt the iterations when a mean square error (MSE) of an output of the soft decision system is below a threshold.

18. The system of claim 10, wherein the turbo equalizer is configured to generate the estimated decisions based further on an estimated noise variance, and where the system further includes:
an adaptive frequency domain noise variance estimator to estimate the noise variance in the frequency domain based on the frequency domain representation of the received signal, the estimated channel frequency response, and a frequency domain representation of a hard decision.

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